

State of
the H E P Theory

§ Introduction
hierarchy problem

§ Supersymmetry

§ Composite Higgs

§ Extra Dimension

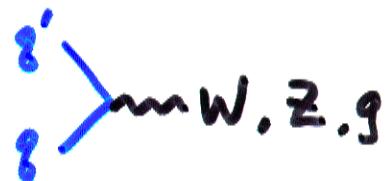
§ Soap Opera

§ Introduction

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$\mathcal{L}_{\text{gauge}}$

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$



well-understood

(even though quantum numbers bizarre)

well-tested

LSP, SLC, NuTeV, CDF, DØ, ...

$\mathcal{L}_{\text{Higgs}}$ Electroweak Symmetry Breaking

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{QCD}}$$

not understood

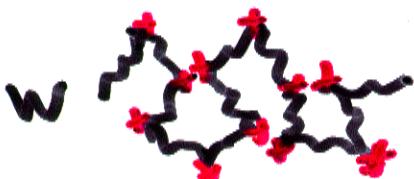
variety of possibilities

supersymmetry, technicolor,

extra dimensions, topcolor, ...

not tested

even though indirect constraints
from precision EW data



δ

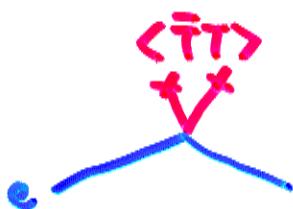
$\mathcal{L}_{\text{Yukawa}}$ Origin of flavor,
fermion masses, mixing
not understood

depends on what $\mathcal{L}_{\text{Higgs}}$ is



Supersymmetry

\Rightarrow approximate flavor symmetry
broken @ M_{GUT}

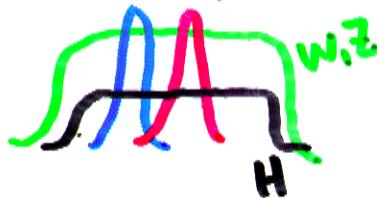


technicolor

\Rightarrow four-Fermi interactions
@ $\sim 100 \text{ TeV}$

$e_L e_R$

extra dimension



\Rightarrow different generations sit
at different locations
inside a "fat" brane

not tested

however, masses well-known
mixings known
FCNC constraints

progress hinges on
physics of Electroweak Symmetry Breaking

progress hinges on physics of Electroweak Symmetry Breaking

Bad News

Fermi $\mathcal{H}_F = \frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^\mu (1 - \gamma_5) \mu^- \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e$

$$G_F \sim (300 \text{ GeV})^{-2}$$

It has been clear since 1933 that something important is going on

@ $E \sim 300 \text{ GeV}$

We still don't know what!

progress hinges on physics of Electroweak Symmetry Breaking

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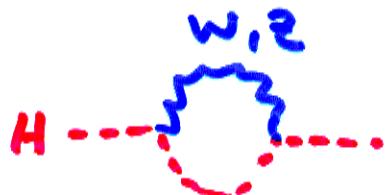
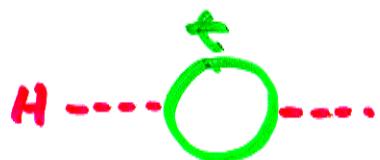
Good News

We are finally getting there!

Tevatron Run II, LHC, e^+e^-LC , VLHC,
 $\mu^+\mu^-$, ...

We definitely need physics beyond the SM
the minimal SM \neq the final theory

- hypercharge assignments bizarre
- anomaly cancelation
- pattern of fermion masses, mixings
esp. small neutrino mass
- Higgs : the only scalar in the SM
introduced just for the EWSB



$$\delta m_H^2 = \frac{3\Lambda^2}{16\pi^2 v^2} (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)$$

large Λ would correct m_H too much
fine-tuning problem

if $\Lambda \sim M_{Pl}$

$$(m_H^2)_0 = 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000 \text{ GeV}^2$$

$$\delta m_H^2 = -1,000,000,000,000,000,000,000,000,000,000,000,000,000,000 \text{ GeV}^2$$

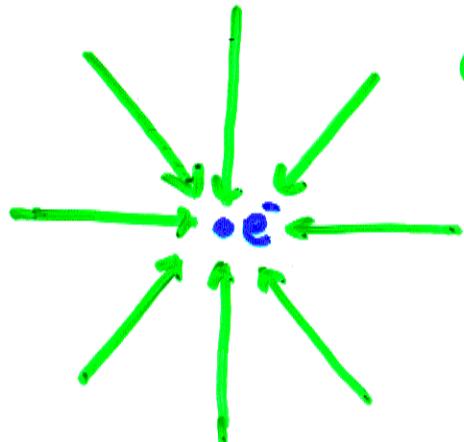
$$(m_H^2)_{\text{tot}} = -9,000 \text{ GeV}^2$$

§ Supersymmetry

revisit δm_H^2

historic example

m_e in $E + M$



Coulomb field

$$\delta m_e c^2 = E_{\text{self}} = \frac{\alpha_{\text{fc}}}{r_e}$$

"size" $r_e \lesssim 10^{-16} \text{ cm} \Rightarrow \delta m_e c^2 \gtrsim 1 \text{ GeV}$

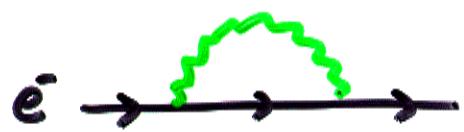
$$(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \delta m_e c^2$$

0.00051	-0.99949	1.00000
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can't possibly be true!

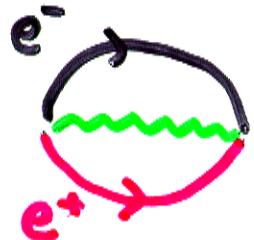
classical $E+M$ not applicable

below $\frac{\alpha_{\text{fc}}}{m_e c^2} \sim 10^{-13} \text{ cm}$

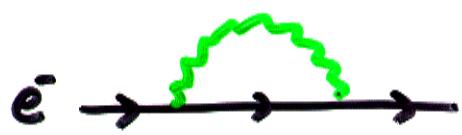


$$\delta m_e c^2 = \frac{\alpha \hbar c}{r_e}$$

however, positron exists

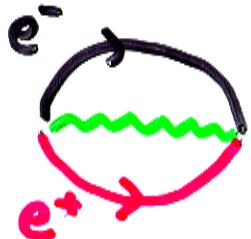


vacuum fluctuation

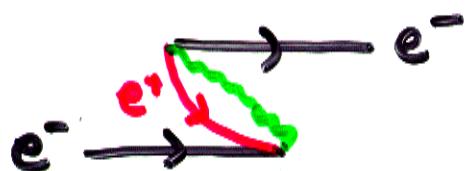


$$\delta m_e c^2 = \frac{\alpha \hbar c}{r_e}$$

however, positron exists



vacuum fluctuation



$$\delta m_e c^2 = -\frac{\alpha \hbar c}{r_e}$$

total: $\delta m_e c^2 \sim \frac{\alpha}{2\pi} m_e c^2 \log \frac{t}{m_e c r_e}$

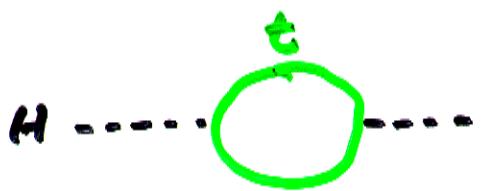
even with $r_e \sim$ Planck length 10^{-33} cm
only 7% correction

doubled # particles

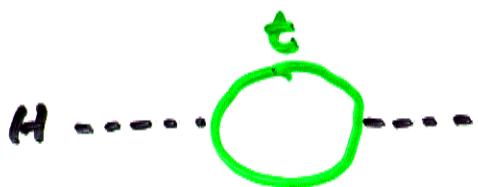
\Rightarrow new symmetry chiral symmetry
 $\psi \rightarrow e^{i\theta \tau_5} \psi$

softly broken by $m_e \neq 0$

$\Rightarrow \delta m_e \propto m_e$

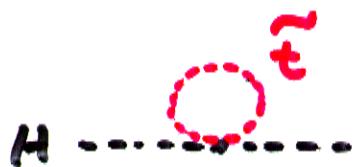


$$\delta m_H^2 \sim -h t \frac{1}{r_H^2}$$



$$\delta m_H^2 \sim -ht^2 \frac{1}{r_H^2}$$

double # particles



$$\delta m_H^2 \sim +ht^2 \frac{1}{r_H^2}$$

$$\text{total: } \delta m_H^2 \sim -(m_{\tilde{t}}^2 - m_t^2) ht^2 \log \frac{1}{m_H r_H}$$

even with $r_H \sim$ Planck length,
no serious fine tuning

if $m_{\tilde{t}} \lesssim$ a few hundreds GeV

new symmetry: supersymmetry

softly broken by: $m_{\tilde{t}} \neq m_t$

in general, $\delta m_H^2 < 0$

\Rightarrow EWNSB

§ Composite Higgs

electron w/ a finite size r_e

$$\Delta m_ec^2 \sim \frac{e^2}{r_e}$$

no fine-tuning if $r_e \gtrsim 10^{-13} \text{ cm}$

similarly, if Higgs boson composite

with a finite size $r_H \gtrsim 10^{-17} \text{ cm}$ OK!

explicit model-building hard in general

FCNC constraints

precision EW data

typically r_H smaller \rightarrow more fine-tuning

\Rightarrow doesn't mean wrong!

probably limited by theorists' imagination

§ Extra Dimension

Very new approach

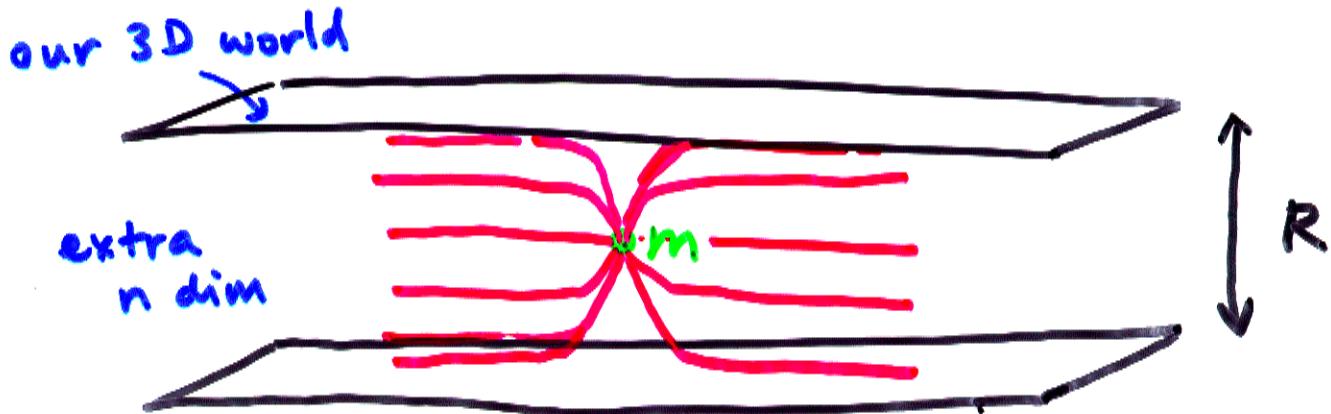
Arkani-Hamed,
Dimopoulos, Dvali (1998)

no physics above $\Lambda \sim 1-10 \text{ TeV}$!

⇒ no fine-tuning problem

What about Planck scale?

$$M_p = (8\pi G_N)^{-1/2} = 2 \times 10^{18} \text{ GeV} \gg \text{TeV}$$



$$r < R \quad g \sim \frac{m}{r^{2+n}} G_N$$

$$r > R \quad g \sim \frac{m}{r^2} \frac{G_N}{R^n} \Rightarrow G_N$$

$G_N \sim (\text{TeV})^{n+2}$ possible!

if $R \sim 1 \text{ mm}$ ($n=2$)

1 fm ($n=6$)

such an interesting, radical possibility
discovered only recently

⇒ may be more possibilities

on physics of EWSB

⇒ settled only by theory/expt interplay

This Decade = Exciting Time

"Fermi's Dream Era"

such an interesting, radical possibility
discovered only recently

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This Decade = Exciting Time

"Fermi's Dream Era"

era of lots of confusion, too.

different subfields will help each other

⇒ an example "story"

This is a work of fiction. Names, characters, places, and incidents are either the product of the speaker's imagination or are used fictitiously, and any resemblance to actual persons, living or dead, experiments, laboratories, events is entirely coincidental.

§ A Soap Opera

'3

supersymmetry

supergravity - med. ~~SUSY~~

discovery @ LHC

Solar ν

Neutrino 2002

KamLAND Evidence for reactor $\bar{\nu}_e$ deficit
 \Rightarrow Large Mixing Angle MSW

SNO Neutral Current data

$$R \equiv \frac{(cc/nc)_{\text{data}}}{(cc/nc)_{\text{MC}}} = 0.71 \pm 0.08$$

$\neq 1$ no osc

$\neq 0.4$ oscillation $\nu_e \rightarrow \nu_{\mu,\tau}$

Borexino ^7Be neutrino

$$\frac{D-N}{D+N} = -0.10 \pm 0.04$$

\Rightarrow Low solution?

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Bahcall-Krastev-Smirnov 2-flavor global fit

no osc soln @ 99% CL

Barger - Pakvasa - Whisnant

can fit the data with 5 ν_s

New Homestake

✓ capture efficiency calibrated

→ old efficiency 15% off

ORNL



→ old cross section 20% off

after extrapolation

to $E_p \ll$ Coulomb barrier

$$\Rightarrow P_{\text{survival}}(v_0) \sim 60-70\%$$

still no soln (Bahcall-Krastev-Smirnov)

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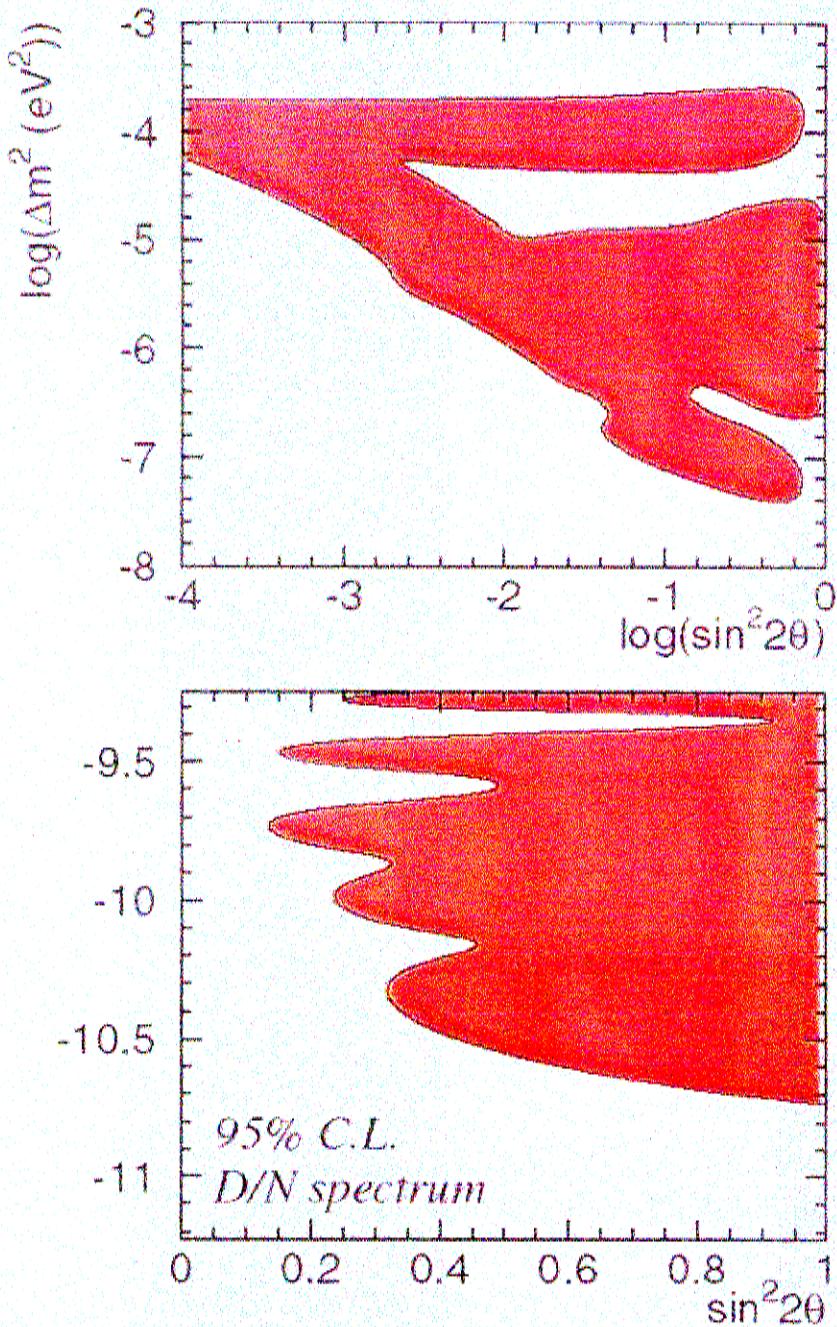
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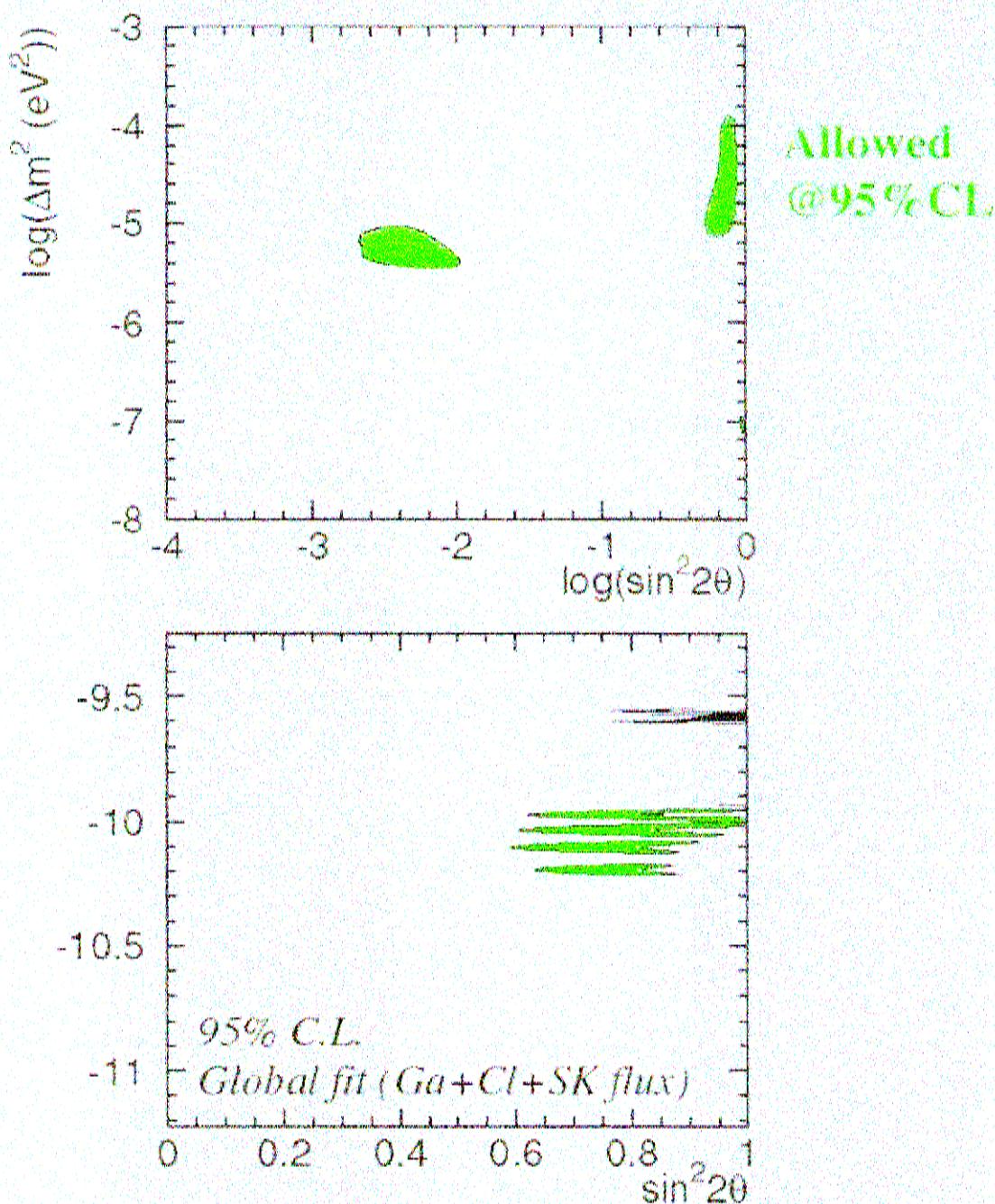
⇒ true soln ~ LMA
but with $\theta = 50^\circ > 45^\circ$
finally solar data converged
 $\nu_e \rightarrow \nu_{\mu,\tau}$ oscillation

Super-Kamiokande

Day/Night+ Spectrum (Active neutrinos)



Flux-global (Cl+Ga+SKflux)



atmospheric ν

2004 K2K Evidence for ν_μ deficit $\sim 3.5\sigma$

SuperK NC π^0 rate (+ K2K near det data)

\Rightarrow consistent w/ $\nu_\mu \rightarrow \nu_e$ not ν_s

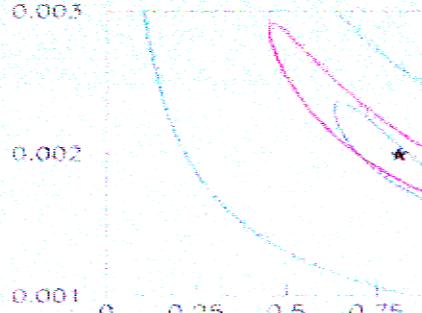
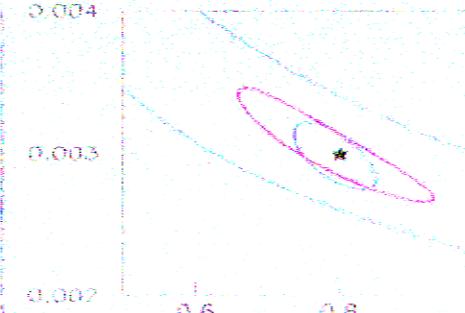
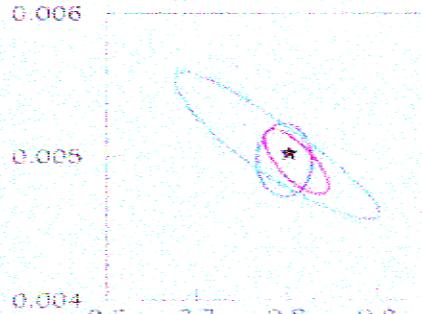
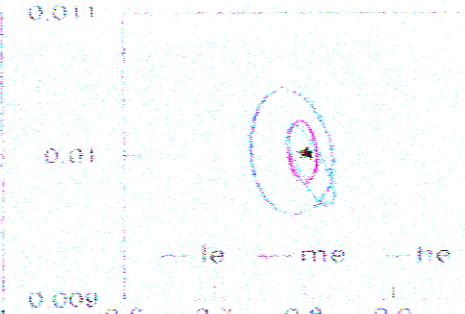
2006 MINOS precise determination of
 $(4m^2, \sin^2 2\theta)$

osc established $> 5\sigma$

NEUTRINO
OSCILLATION

MINOS

arXiv

eV² $\Delta m^2 = 0.002 \text{ eV}^2$  $\Delta m^2 = 0.003 \text{ eV}^2$  $\Delta m^2 = 0.005 \text{ eV}^2$  $\Delta m^2 = 0.01 \text{ eV}^2$ 

CC Energy Spectrum
68% Contours
10kt-yr exposure

Mini-BooNE

rules out LSND region @ 4σ

MINOS

excess in NC/CC possibly due to $\nu_\mu \rightarrow \nu_e$

$$\text{fit} \Rightarrow \sin^2 \theta_{13} = 0.04^{+0.018}_{-0.010} \neq 0$$

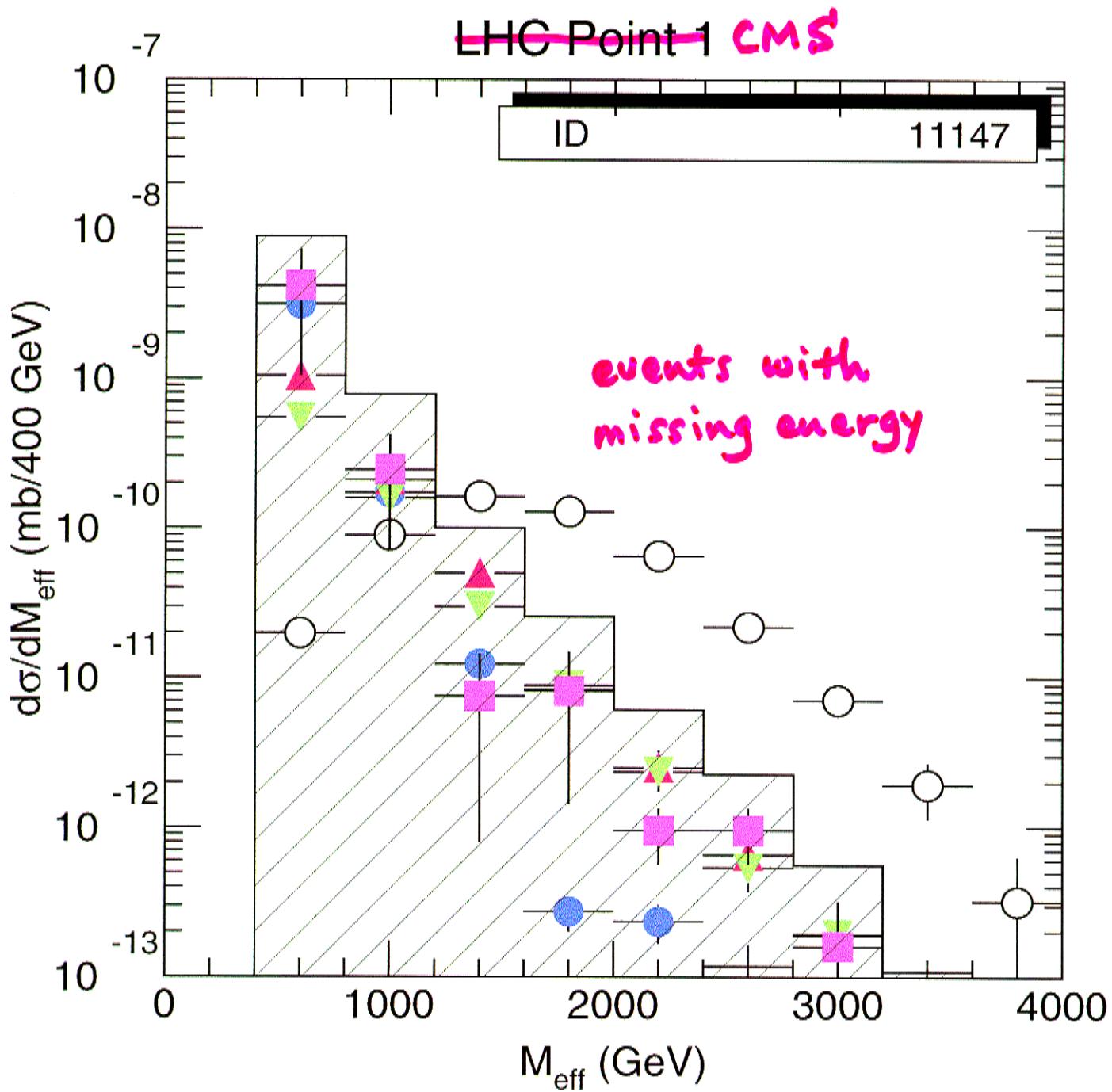
KamLAND

$\sin^2 \theta_{13} < 0.035$ @ 90% CL, high cm^2

unsettled → neutrino factory

key-physics: 12 neutrino mass models/day

Lepton Photon 2007



somewhat, no Higgs boson signature

$\cancel{E}_T + \tau's$

SUSY

vs

technicolor

$\tilde{g}, \tilde{\chi}$

color-octet PGB

$\tilde{\chi}^0, \tilde{\chi}^\pm$

color-singlet PGB

SUGRA w/

no concrete model

large $\tan\beta$?

⇒ doesn't fit the data well.

LANL archive August 4, 2007

hep-ph/0708245 Kane et al

hep-ph/0708246 Lane et al

hep-ph/0708247 Dimopoulos et al

hep-ph/0708248 Chivukula et al

hep-ph/0708249 Giudice et al

hep-ph/0708250 Appelquist et al

hep-ph/0708251 Hall et al

hep-ph/0708252 Georgi et al

Debeda

Great

The

LHC + Tevatron

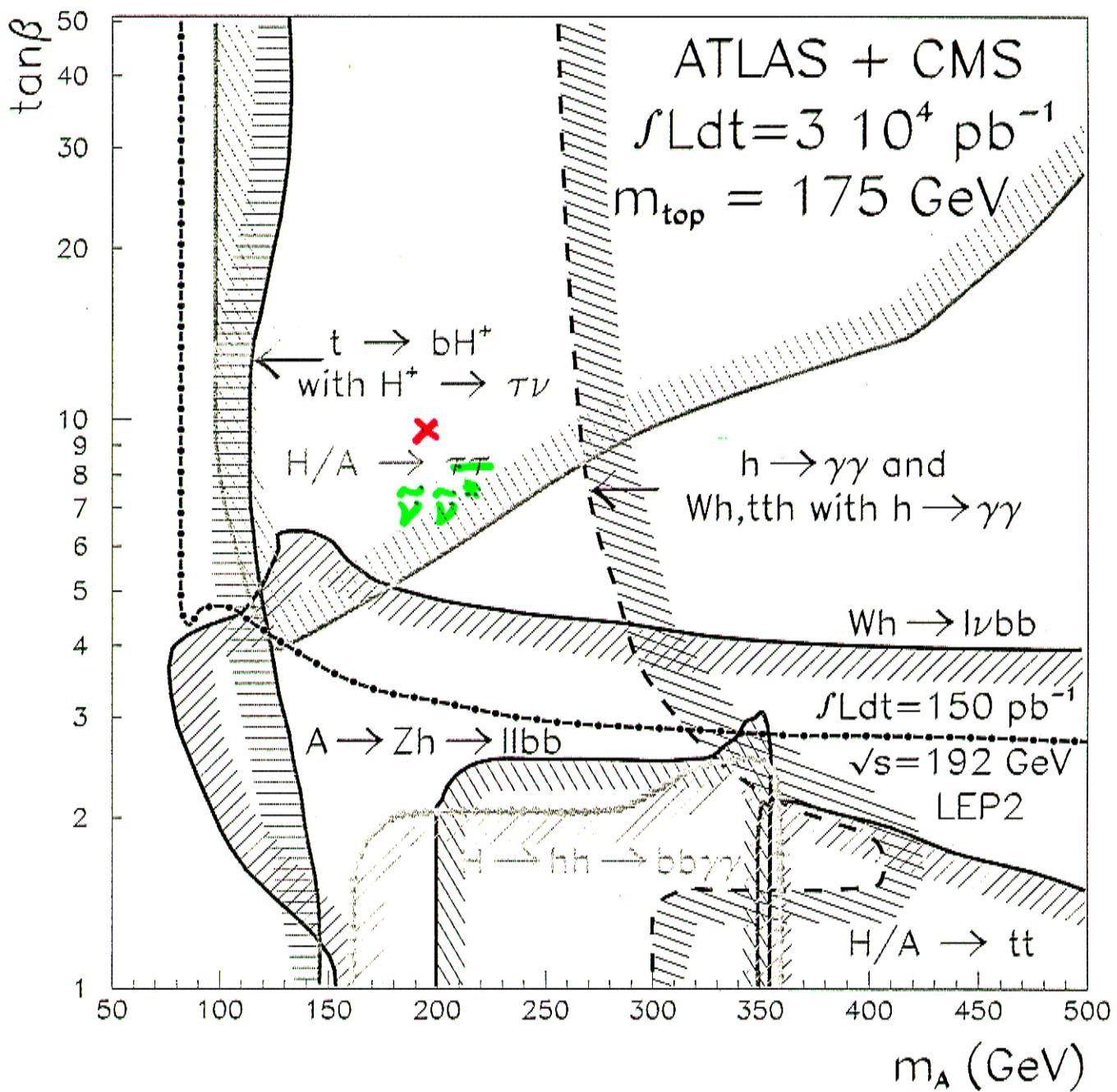
excess in $\gamma + \not{E}_T$, $\gamma\gamma + \not{E}_T$

gauge med?
extra D?
technipions?

LHC + Tevatron

excess in $\gamma + \cancel{E}_T$, $\gamma\gamma + \cancel{E}_T$

gauge med?
extra D?
technipions

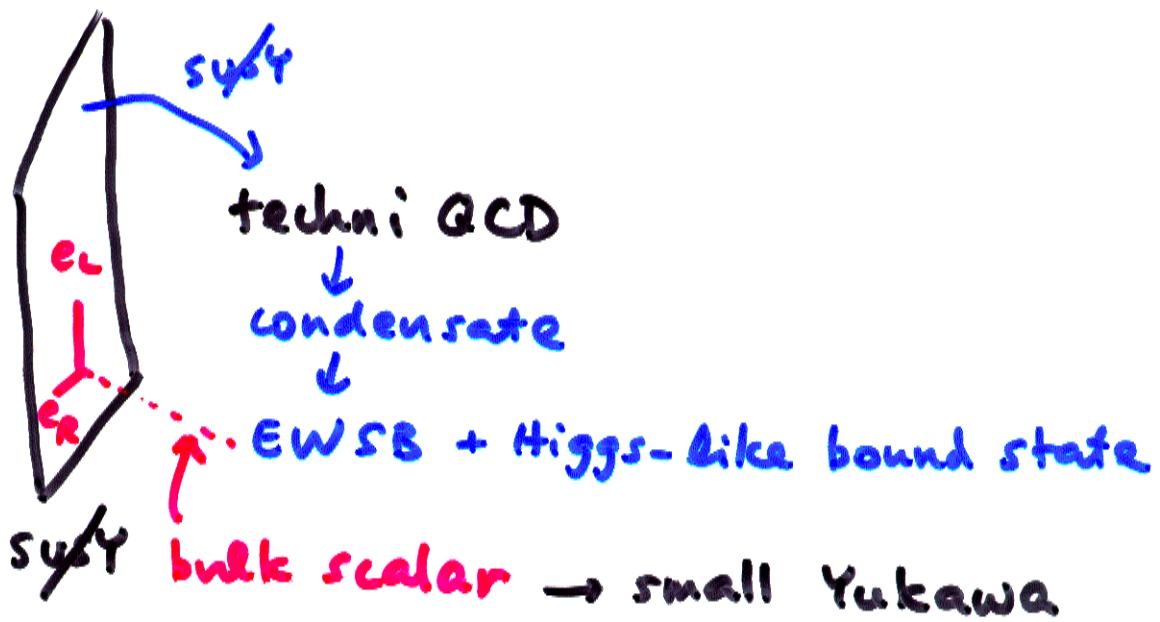


Lykken et al

Giudice et al

Okada et al

supersymmetry-assisted technicolor
w/ gauge mediation on our brane
techni-gauge bosons in the bulk



+ topcolor interaction \rightarrow large M_t

$$R_{2D} \approx 200 \mu\text{m} \begin{array}{l} +100 \\ -50 \end{array} \quad \text{best fit}$$

Tevatron

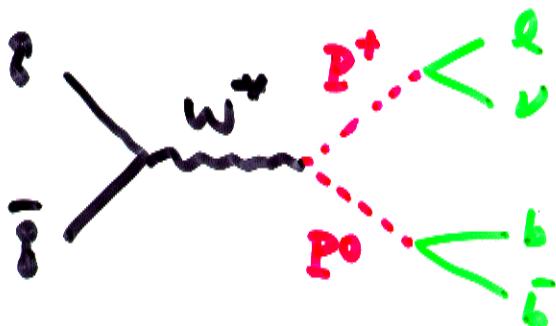
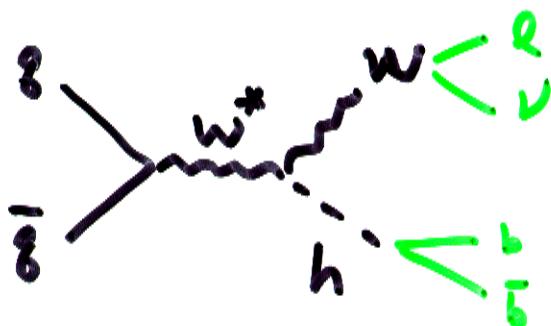
$20\text{fb}^{-1}/\text{expt}$

$$W h \rightarrow b\bar{b}$$
$$\downarrow \rightarrow q\bar{q}$$

"Evidence for a $b\bar{b}$ mass peak
in association with a W-boson"

Abe et al

@ 3σ



e^+e^- LC @ $\sqrt{s} = 91$ GeV

$10^9 Z$ "Giga Z"

$A_{LR}, A_b, A_c, R_b, R_c, A_{LR,FB}^{\gamma}, \dots$

charm fragmentation fu into γ
differs from LEP $\sim 2\sigma$

I. Stravinsky

"Reanalysis of Charm Fragmentation Fns"

.... which may be relevant to the
recent high-energy data ...

H. Bethe

Brief Comment in PRD

$c \rightarrow \gamma$ could explain $\tau's + \cancel{E}_T$ data

Tevatron remeasures PDF @ high x

K. Ellis et al NNNLO calc of $8\bar{8} \rightarrow \gamma X$

$\tau's + \cancel{E}_T$ excess goes away

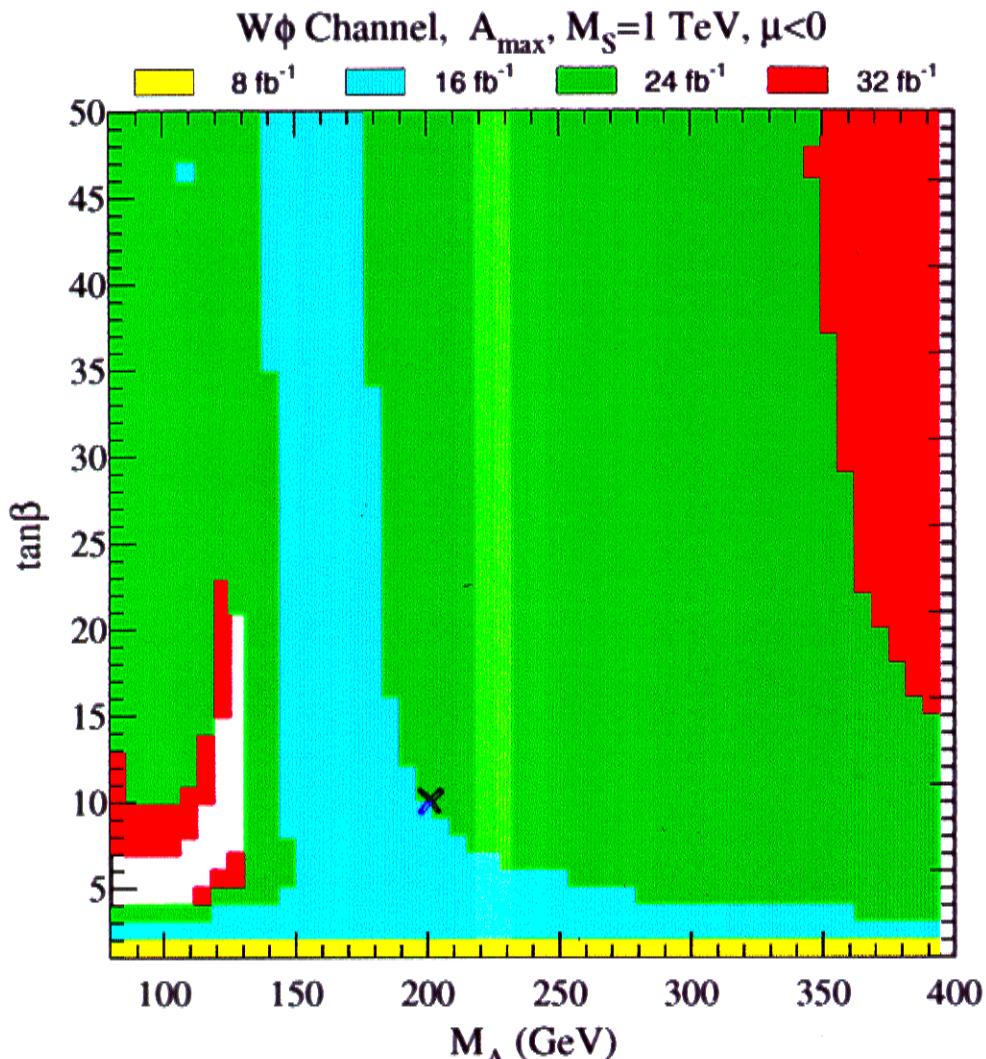
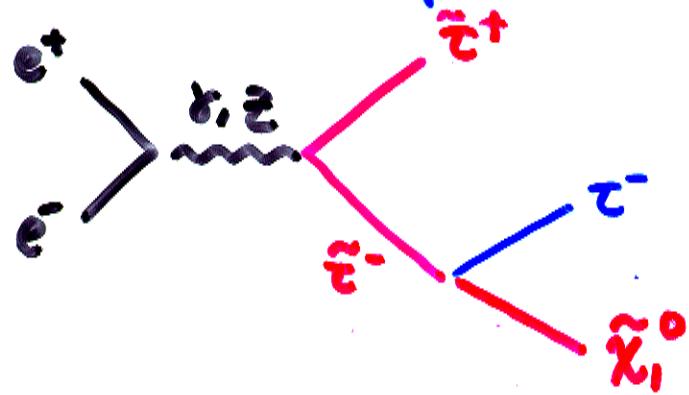


FIG. 3. 5σ discovery contours for the $W\phi(\rightarrow b\bar{b})$ mode at the Tevatron in the MSSM for maximal mixing, $\mu < 0$, and $M_S=1$ TeV. Different shadings correspond to different integrated luminosities.

LC $\sqrt{s} = 300 \text{ GeV}$

$$e^+ e^- \rightarrow \tau^+ \tau^- \notin$$

standard interpretation

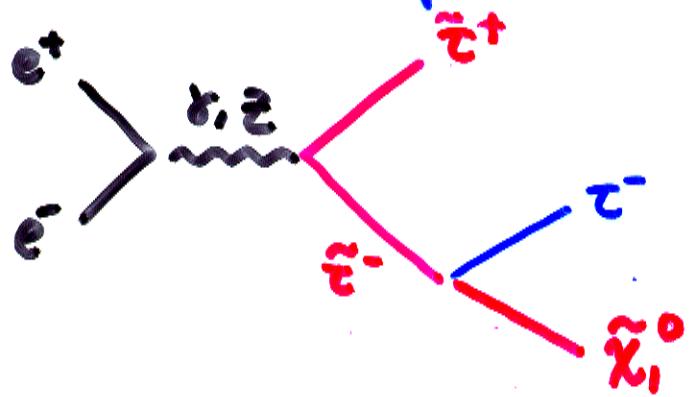


however, threshold scan $\Rightarrow \beta \text{ not } \beta^3$

LC $\sqrt{s} = 300 \text{ GeV}$

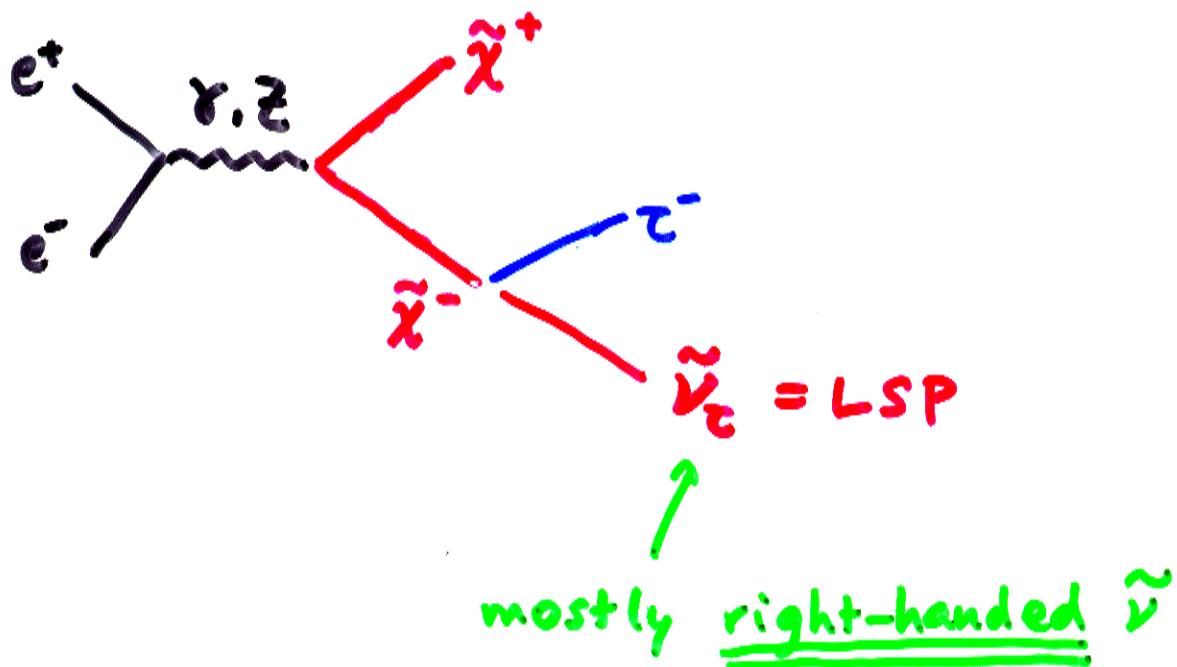
$$e^+ e^- \rightarrow \tau^+ \tau^- \notin$$

standard interpretation



however, threshold scan $\Rightarrow \beta \text{ not } \beta^3$

correct interpretation



MSSM + $\tilde{\nu}_R \times 3$

$\tilde{\nu}_{\text{CR}} \approx \text{LSP}$

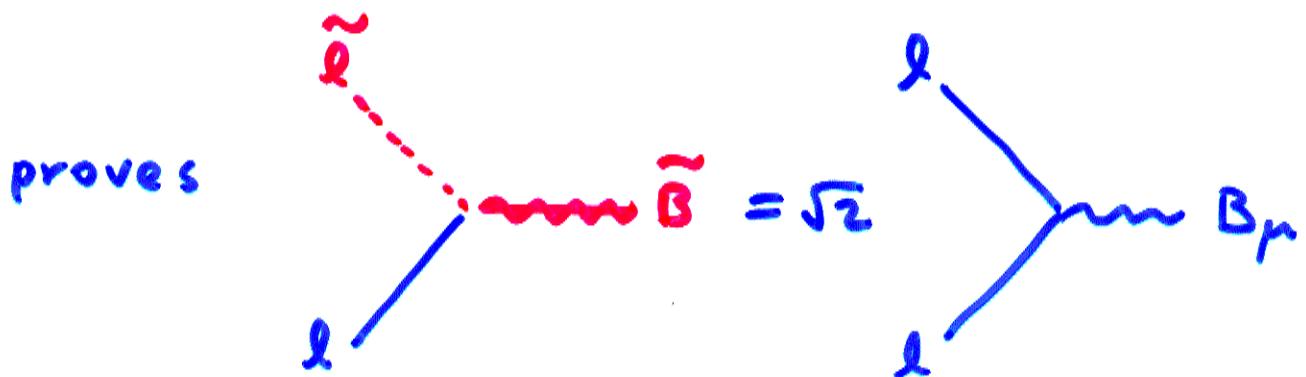
$\Rightarrow \tau$ -dominant SUSY signature

bigger ℓ_T

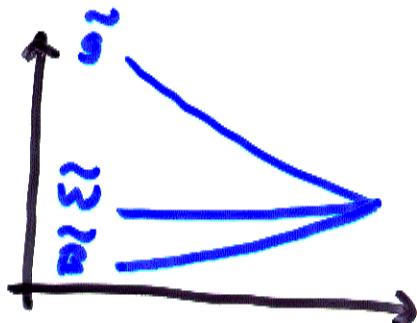
chargino \leftrightarrow stau

\Rightarrow eventually explains the data

LC



LHC + LC $M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} \approx 1 : 2 : 7$



GUT?

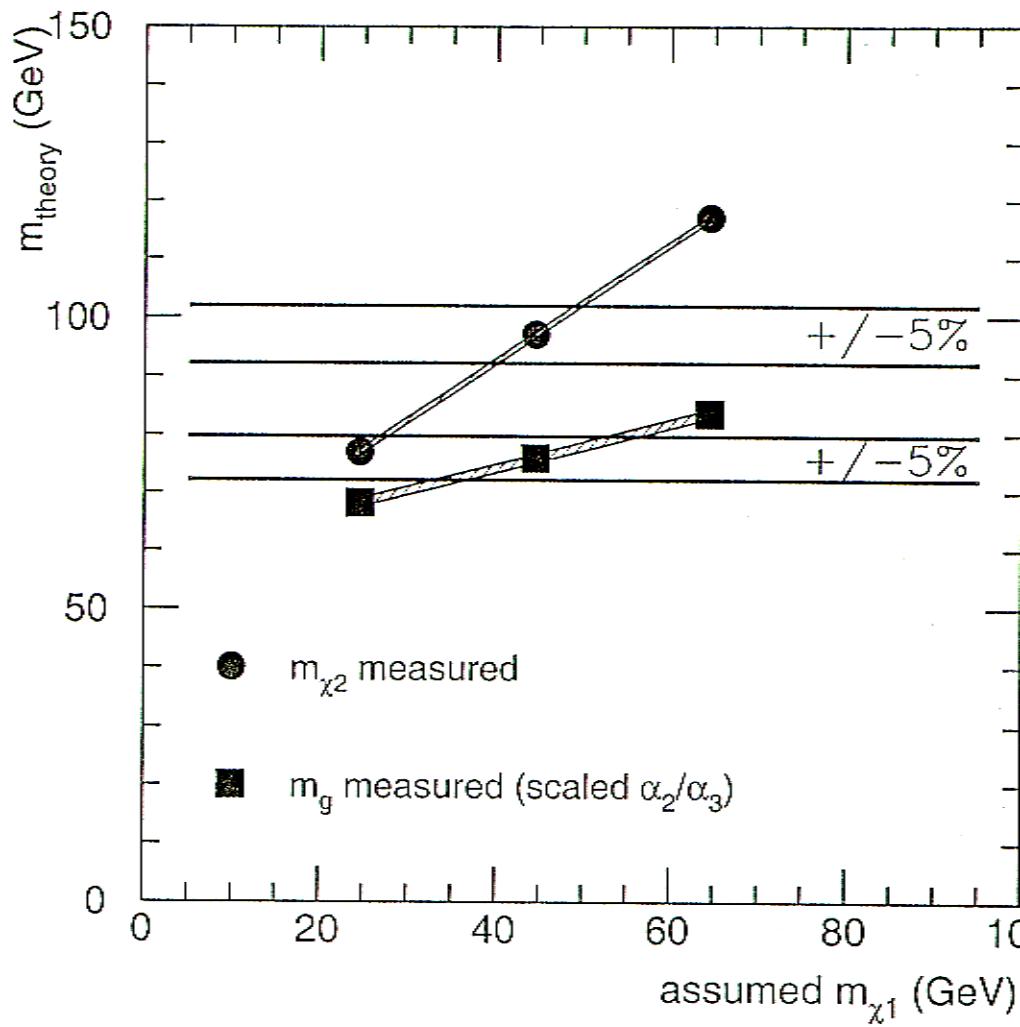
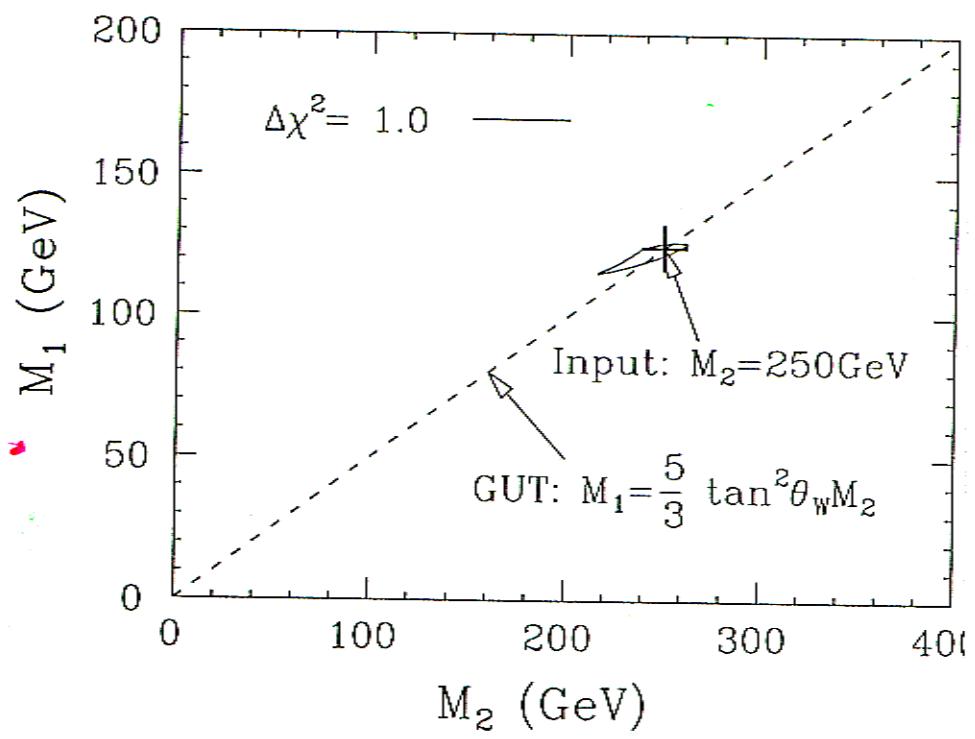
gauge mediation?

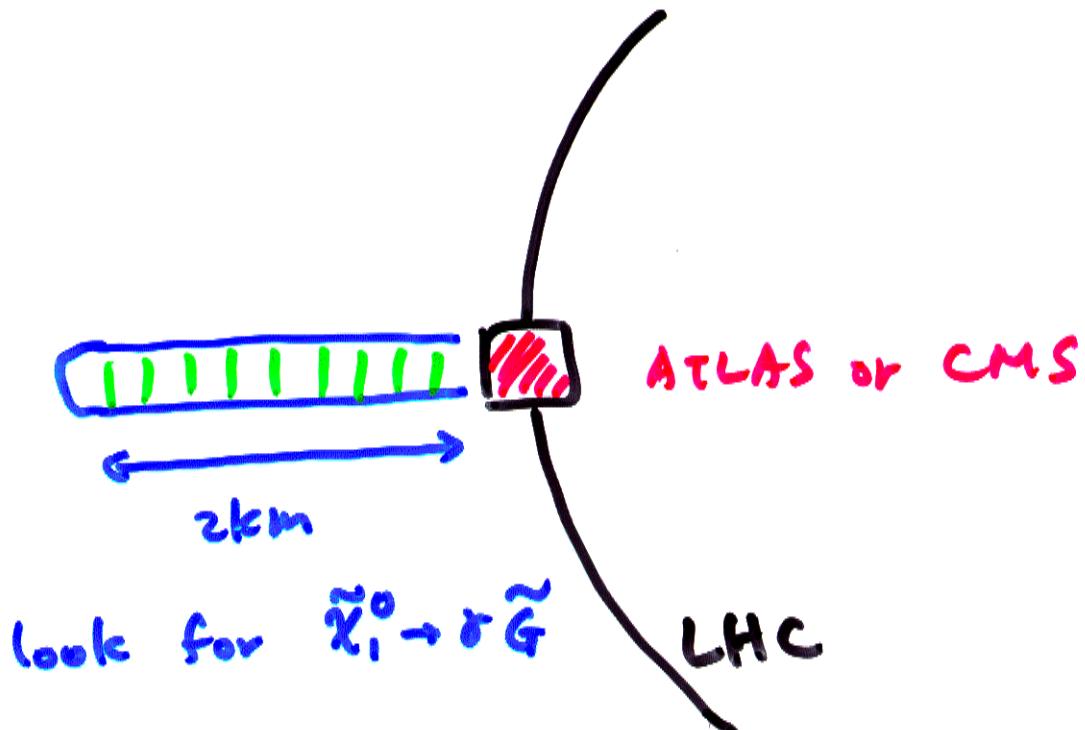
gaugino mediation?

anomaly mediation

Hinchliffe, Paige

Tsukamoto, Fujii, IIM





$$\Rightarrow \sqrt{F_{\text{Susy}}} > 1,800 \text{ TeV}$$

LHC + LC

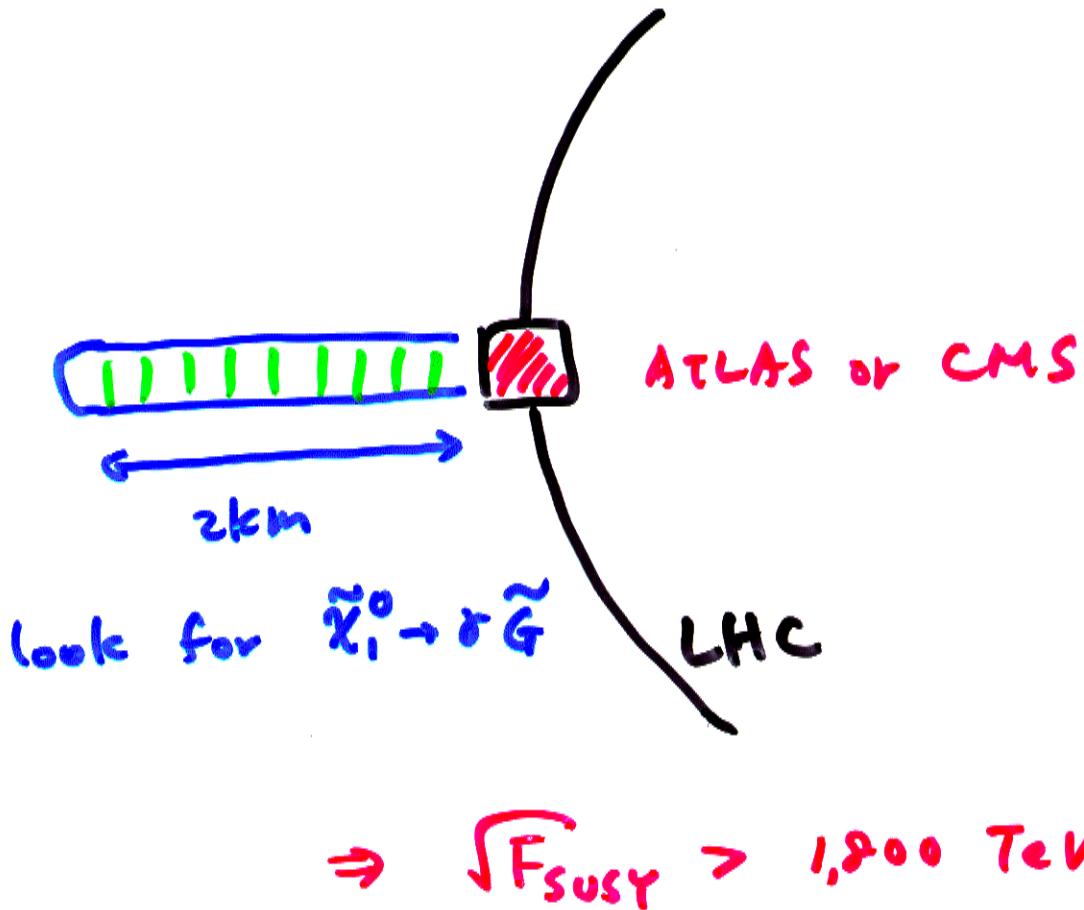
scalar spectrum

$$(\tilde{e}_R, \tilde{e}_L, \tilde{\nu}, \tilde{u}_R, \tilde{d}_R, \tilde{u}_L, \tilde{d}_L)$$

GUT?

gauge mediation?

takes time to reduce errors



$$\Rightarrow \sqrt{F_{\text{SUSY}}} > 1,800 \text{ TeV}$$

LHC + LC

scalar spectrum

$$(\tilde{t}_R, \tilde{t}_L, \tilde{v}, \tilde{u}_R, \tilde{d}_R, \tilde{u}_L, \tilde{d}_L)$$

GUT?

gauge mediation?

takes time to reduce errors

heavy states still missing

VLHC + $\mu^+ \mu^-$

ICHEP 2004

CDF / DØ / BABAR / BELLE $B_d \rightarrow J/\psi K_S$

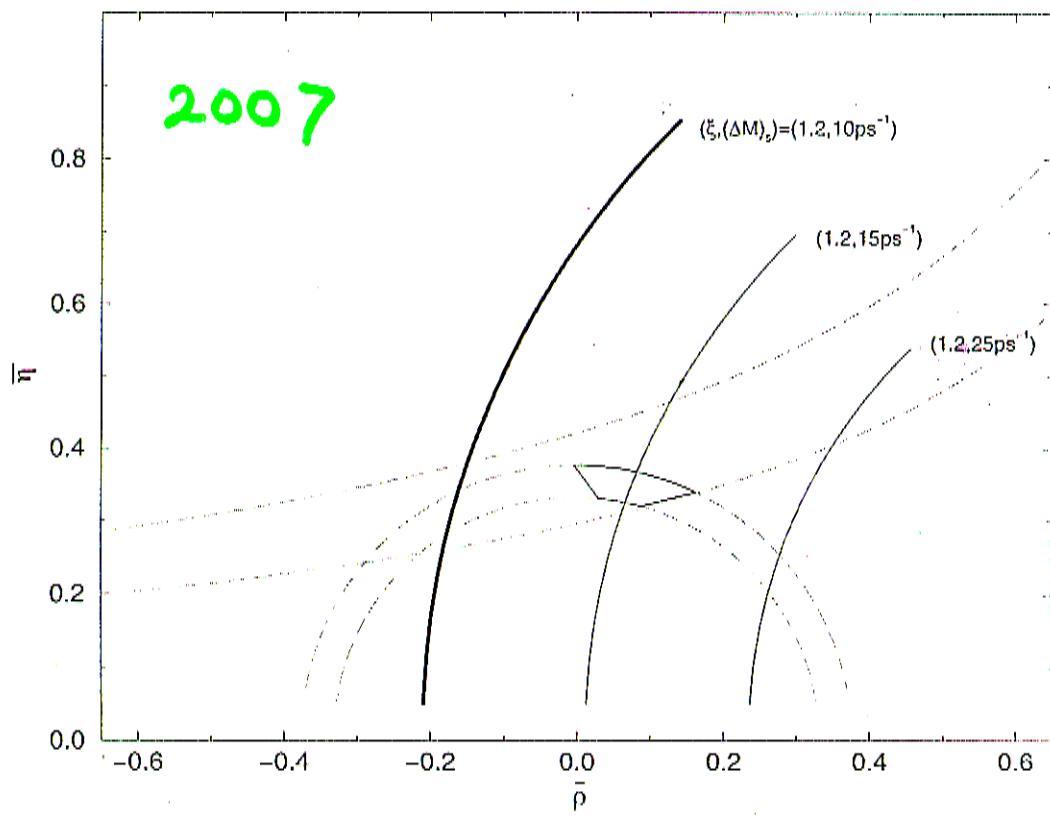
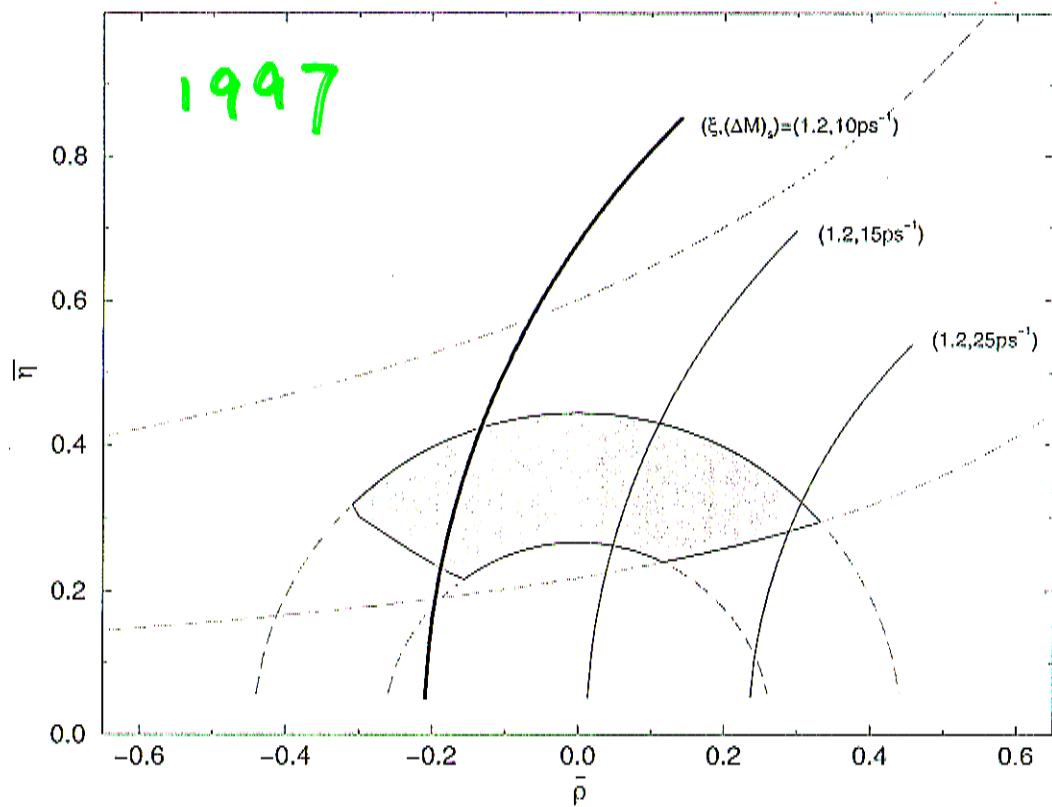
$$(\sin 2\beta)_{W.A.} = 0.62 \pm 0.18$$

BNL $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ $\Rightarrow \text{Im } V_{td}$

\Rightarrow beautiful agreement

with the Standard Kobayashi-Maskawa
theory

Buras



ICHEP 2004

CDF / DØ / BABAR / BELLE $B_d \rightarrow J/\psi K_S$

$$(\sin 2\beta)_{W.A.} = 0.62 \pm 0.18$$

BNL $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ $\Rightarrow \text{Im } V_{td}$

\Rightarrow beautiful agreement

with the Standard Kobayashi-Maskawa
theory

2008

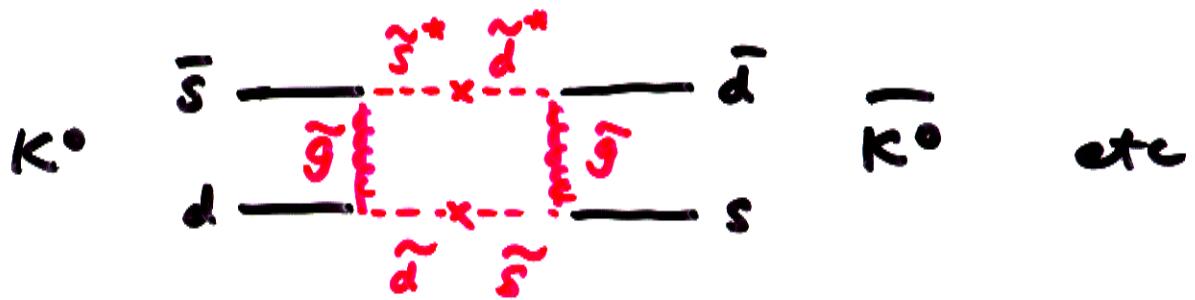
BTeV / LHC-B

$B_s \rightarrow \rho K_S$ $\sin 2\gamma$

KM theory: wrong discrete choice

$$\sin 2\beta = \sin 2\left(\frac{\pi}{2} - \beta\right)$$

global fit with SUSY contributions



\Rightarrow 0(80) SUSY flavor parameters

+ quark masses, CKM matrix

+ lepton masses MNS matrix
neutrino masses

\Rightarrow flavor physics

low-energy expts

μ -e conversion

rare K decays

etc

Lattice QCD

hadronic matrix elements

\Rightarrow models of flavor GUT? string?

Sloan DSS + MAP + Planck

$$\sim 2008 \quad \Omega_M = 0.35 \pm 0.02$$

$$\Omega_{\text{tot}} = 1.01 \pm 0.02$$

$$\Omega_{\text{dark energy}} = 0.66 \pm 0.03$$

SNAP

$$w = -0.99 \pm 0.09 \quad \rightarrow \text{eq. of state } p/\rho$$

\Rightarrow cosmological constant $w = -1$

dark energy: energy density
which doesn't get diluted
even though Universe expands

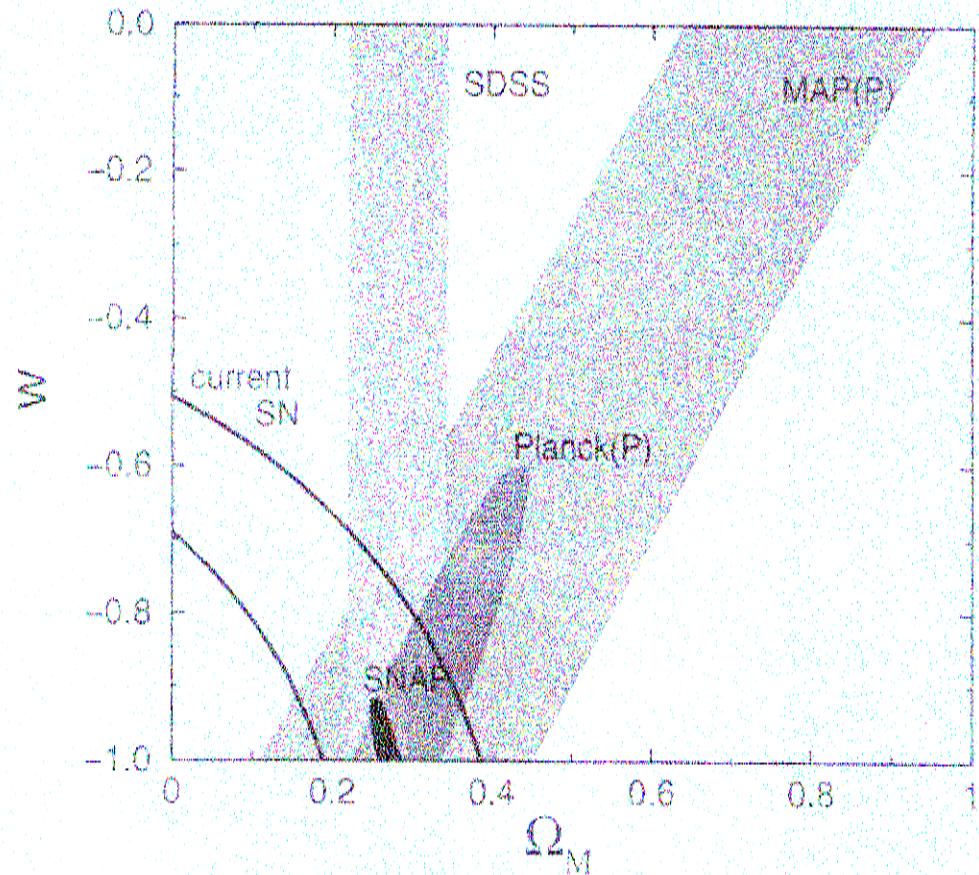


Figure 1: SNAP constraint on parameters Ω_M and w compared to those of MAP and Planck both with polarization information and SDSS (MAP, Planck and SDSS constraints are from [37]). Also shown are the present constraints using a total of 45 SN. All constraints are 1 σ and include statistical uncertainties only. A flat universe is assumed, and fiducial values of the parameters are taken as $\Lambda = \Omega_{\Lambda_0} = 0.28$, $n = 1$. MAP and SDSS constraint regions are obtained using a Fisher matrix analysis, while SNAP constraint is obtained using a Monte Carlo simulation.

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Al Gore:

Not only I'd created the Internet,

I've funded the discovery of

a source of energy that doesn't dry up.

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$$\Rightarrow \text{cosmological } \underline{\text{constant}} \quad w = -1$$

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Senate Security Committee

probe if a harddisk had ever
been misplaced @ LBNL

superstring :

- ~1972 birth
- ~1984 anomaly cancellation
- ~1996 duality
- ~2008 non-perturbative string soln
in the de Sitter BG
 $\Lambda \neq 0$

Banks - Kachru - Silverstein

$$\Lambda \neq 0 \rightarrow m_{SUSY}^4 \propto \Lambda^{y_2}$$

$$m_{SUSY} \sim 1 \text{ TeV}$$

$$\Lambda \sim \left(\frac{\text{TeV}^2}{M_{Pl}} \right)^4 = \left(\frac{1}{2} \text{ meV} \right)^4$$

$$\text{data} \Rightarrow \Lambda = (2 \text{ meV})^4$$

LHC + LC \rightarrow SUSY spectrum

CDMS, ICECUBE, GENIUS, ... \rightarrow DM cross section

Planck surveyor $\rightarrow \Omega_{\text{CDM}}$

not consistent w/ each other

phase transition @ $T \sim 1 \text{ GeV}$?

string moduli decay?

evaporating primordial BH?

extra dimension?

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factor of $\frac{1}{2!}$ missing in σ_{ann} in DM MC

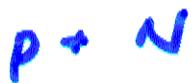
"I've misled people but I didn't lie."

Murayama

balloon-borne
space station-based ^{expts}

primary cosmic ray flux $\pm 5\%$
over the entire solar cycle

new low-energy expts @ JHF



$$p + O \quad E_p = 1 \sim 30 \text{ GeV}$$



\Rightarrow atmospheric $\nu \pm 10\%$

2018 HyperKamiokande

$(100\text{m})^3 \frac{1\text{ Mt}}{1\text{ Tg}}$ Water Čerenkov

reports 20 events vs 5 ± 0.5 BG

$\rho \rightarrow e^+ \pi^0$ $\tau \sim 10^{35} \text{ yrs}$

but no $\bar{\nu} K^+$ mode expected
in SUSY GUT

???

HAVE FUN !